Prepared in cooperation with cience for a changing world U.S. Geological Survey Portland State University, Shannon and Wilson, Inc., and the Tri-County Metropolitan Transportation District of Oregon

INTRODUCTION The Tualatin Mountains form a northwest-striking ridge about 350 m high that separates Portland, Oregon, from the cities of the Tualatin Valley to the west. Known informally as the Portland Hills, the ridge is a late Cenozoic anticline, bounded by reverse faults that dip toward the anticlinal axis (figs. 1–3; Beeson and others, 1991; Blakely and others, 1995, 2004; Madin and others, 2008; Peterson and Squier Associates, 1993). The anticline is a broad, open fold consisting chiefly of Miocene Columbia River Basalt Group, with remnants of Miocene-Pliocene Troutdale Formation and Pleistocene basalt of the Boring Volcanic Field on the flanks of the anticline (Beeson and others, 1991, Madin and others, 2008). Anticlinal structures similar to the Tualatin Mountains are characteristic of the northern Willamette Valley (fig. 1), where the structures accommodate margin-parallel shortening of the Cascadia fore arc. Global Positioning System (GPS) results indicate that the shortening is due to the northward motion of Oregon at several millimeters per year with respect to stable North America (McCaffrey and others, 2007). Some of the uplifts may contain active faults, but the structures are

Between 1993 and 1998, construction of the 3-mile-long (4500-m-long) TriMet MAX Light Rail tunnel through the Tualatin Mountains (figs. 2 and 3) provided an unusual opportunity to investigate the geological structure and history of the Tualatin Mountains (Peterson and Squier Associates, 1993; Peterson and Walsh, 1996; Walsh and others, 1996). This report is a collaborative effort among the tunnel geologists and the U.S. Geological Survey (USGS) to document the geologic story and quantify late Cenozoic and Quaternary deformation rates of the Tualatin Mountains.

Figure 1. A. Index map of the Portland (P), Tualatin (T), Northern Willamette red circles; "beachball" shows oblique dextral thrust focal mechanism of M 5.6

(NW), and Southern Willamette (SW) subbasins in the Willamette Valley, and the Columbia Plateau (CP) and the Columbia Gorge (CG); box shows area of figure 1B. **B**. Regional geologic setting and seismicity of the northern Willamette Valley and the Portland basin (modified from Blakely and others, 2000). Seismicity shown by Scotts Mills earthquake. Uplifts and faults include the Chehalem Mountains; Cooper Mountain; Parrett Mountain; Sylvan Fault; Beaverton Fault, Portland Hills Fault, Gales Creek Fault; Mount Angel Fault. Inset shows location of figure 2 centered on

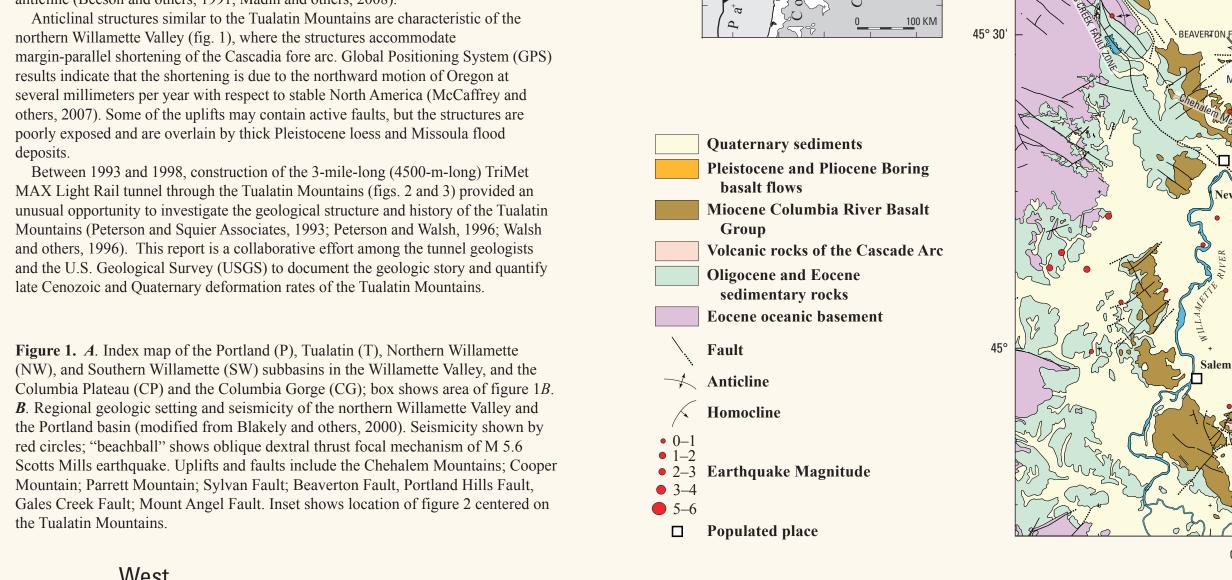


Figure 2. Tualatin Mountains, location of light-rail tunnel (red line), and selected faults (dashed lines where approximately located, dotted where concealed). Numbers along tunnel represent fault zones observed in tunnel and on profile below: (1) West Sylvan, (2) Central Sylvan, (3) East Sylvan, (4) Brickworks, (5) unnamed fault. Figure modified from Blakely and others (2004), after Beeson and others (1989b, 1991) and Madin (1990). Elevation, in meters

B-538 B-19 B-13 B-555 B-537

concrete

o improve our understanding of Quaternary faulting and folding in the Portland Hills, we have compiled a geologic cross section (below) of the Tualatin Mountains. The cross section was compiled from several sources: (1) Expected tunnel geology based on 90 borings totaling 15,000 linear feet (4572 m; at 0.3048 m per foot) along the tunnel route prior to construction (Peterson and Squier Associates, 1993); (2) Unpublished geologic mapping of the tunnel bores by Ken Walsh, who was a geologist with Parsons Brinkerhoff Construction and graduate student working on the tunnel at Portland State University with Professor Marvin Beeson (both now deceased; shown in fig. 4, right); and (3) Stratigraphy, geochronology, geochemistry, and magnetic polarity of Boring basalt flows, structural mapping of the Sylvan Fault, and video of tunnel geology, all gathered by USGS scientists in the tunnel. Geologic units encountered in the tunnel and boreholes were described in the tunnel report (Peterson and Squier Associates, 1993) and the maps of Beeson and others (1991, 1989b) and Madin and others (2008). A core from the exploratory borings is on display at the Washington Park MAX Light Rail Station. This is the deepest station in North America, and it is also a stop on a geological field trip of the city accessible by public transportation (Madin, 2009). The Description of Map Units is modified from the above sources, augmented by Walsh's field notes and USGS field mapping. Geologic profile coordinates are in feet, following the original design for the tunnel. A gravity survey was also made through the tunnel by the USGS and Portland State University, and its interpretation was published in Blakely and others (2004). Structural mapping of the Sylvan Fault in this report is based on USGS mapping and interpretation of tunnel geology. The structural history and the deeper structures are based on the USGS interpretation of the mapped tunnel, borehole geology, and geophysics, and the earlier work of Beeson and others (1991) and Peterson and Squier The resulting deformation history provides an improved understanding of Quaternary faulting and folding in the Portland Hills. Quaternary slip

AN INSIDE VIEW OF THE TUALATIN MOUNTAINS

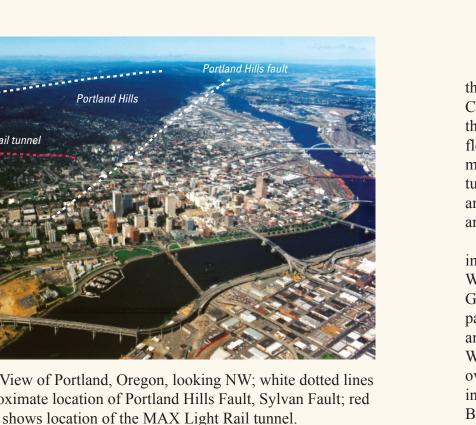


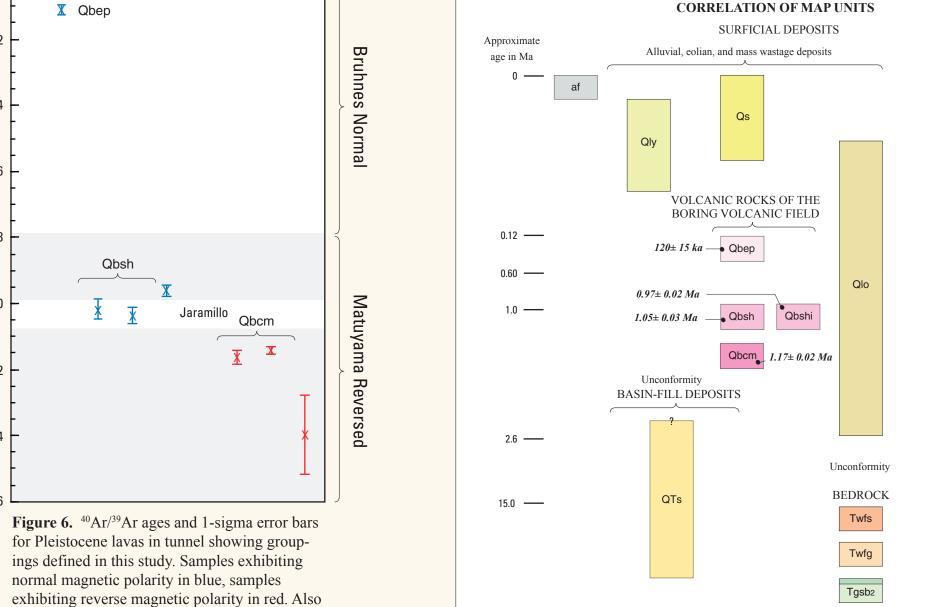
Figure 3. View of Portland, Oregon, looking NW; white dotted lines show approximate location of Portland Hills Fault, Sylvan Fault; red dotted line shows location of the MAX Light Rail tunnel.

The rock units exposed in the tunnel and exploratory borings consist of three main units: (1) Flood-basalt flows of the 15- to 16- million-year-old Columbia River Basalt Group, which make up most of the rocks exposed in the tunnel (green, blue, and orange on the cross sections); (2) younger basalt Tows of the Boring Volcanic Field of Evarts and others (2009), about 1.2 nillion years old to 120,000 years old, exposed in the western third of the unnel (shades of pink on the cross sections); and (3) fine-grained sand, silt and clay interbedded with the Boring basalts and deposited by local streams

STRATIGRAPHIC FRAMEWORK

The uppermost unit, mapped as basaltic andesite of Elk Point (Qbep), is a basaltic andesite flow that fills a channel along the scarp formed by the West Sylvan Fault. Unit **Qbep** crops out at the surface a few kilometers west and south of the tunnel. Elk Point, a prominent conical hill directly north of the tunnel, is inferred to be the vent for this flow. The flow has normal magnetic polarity and yielded an Ar/Ar plateau age of 120±15 ka, making it one of the youngest flows of the Boring Volcanic Field (table 1). The other Pleistocene flows in the tunnel are older than the basaltic andesite of Elk Point, and do not correspond to any flows exposed at the surface nearby. They are mapped as correlative to the basalt of Sunset Hill (Qbsh) and the basalt of Cornell Mountain (Qbcm) (R.C. Evarts, unpub. data; Madin and others, 2008). The tunnel slices through the center of the basalt of Sunset Hill vent complex, which consists of a pile of breccia and cinders 65 m high, which is intruded by a large dike and interfingers with flows thinning away

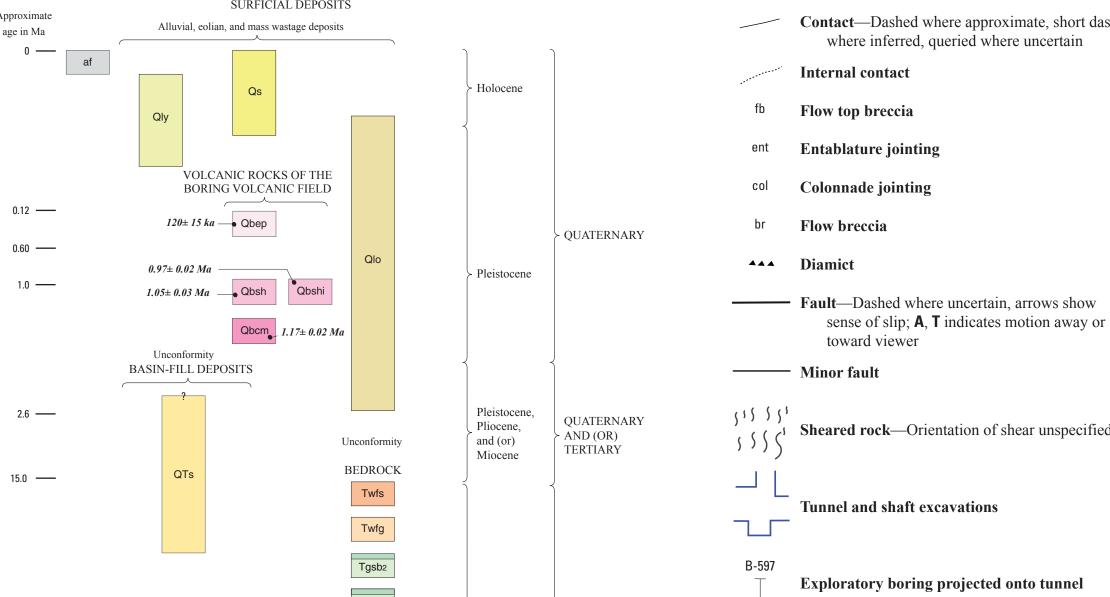
Figure 5. A. Altered flow-top breccia at contact between two Grande Ronde Basalt flows near survey station 825+00. B. Weathered Grande Ronde Basalt cobble diamict (slope collu vium or debris flow?) faulted against vertical, pebbly, firm, gray mudstone at survey station 115+30. C. Steeply dipping red and gray pebbly mudstone near survey station 814+00. shown are Bruhnes Chron (normal polarity,

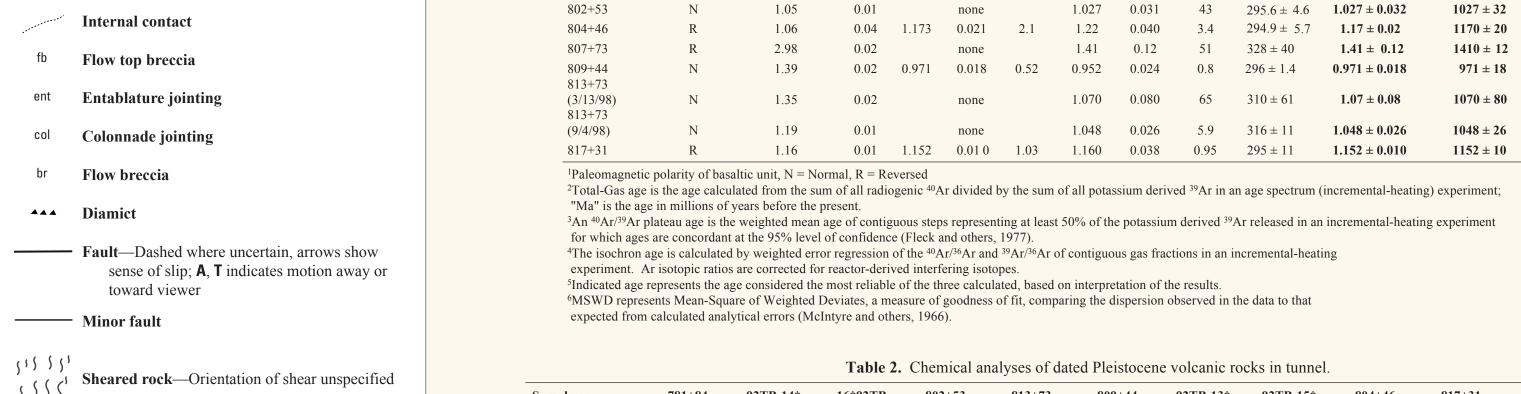


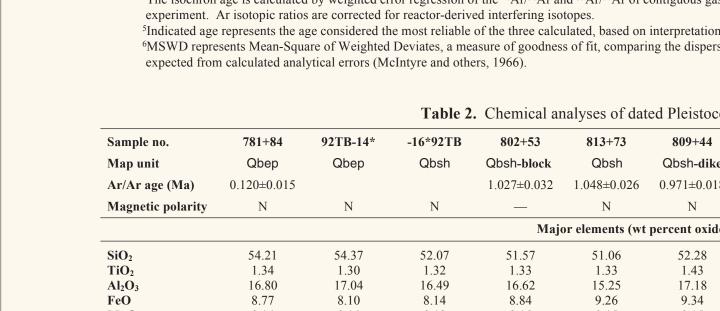
⁴⁰Ar/³⁹Ar ages shown are from table 1

white), Matuyama Chron (reversed polarity,

gray), and Jaramillo Subchron (normal polarity,







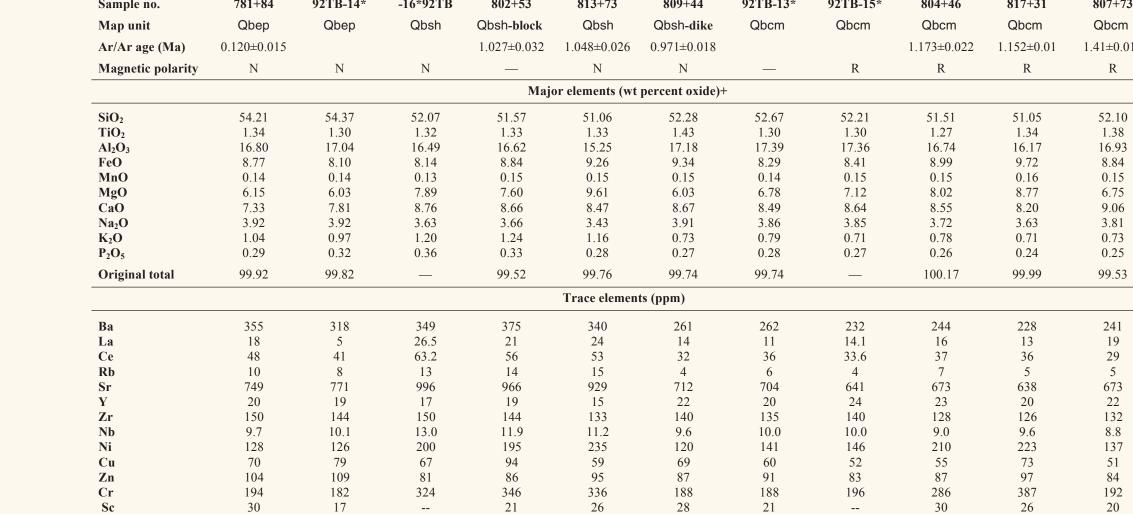


Table 1. 40 Ar/39 Ar ages from Pleistocene basalt flows in the Light Rail Tunnel, Portland Hills, Portland, Oregon.

Age ±1s Age ±1s ⁶MSWD Age ±1s ⁶MSWD Intercept

781+84 N 0.17 0.03 0.138 0.004 1.4 0.120 0.015 1.02 299.1 ± 2.7 **0.120 \pm 0.015 120 \pm 15**

³Plateau Age (Ma) ⁴Isochron Age (Ma) ⁵Indicated age (Ma) Indicated age (ka)

 120 ± 15 ka Age of lava flow in thousands of years (ka); see table 2 100 feet = 30.48 meters vertical exaggeration 2:1

FOLDING AND FAULTING OF THE TUALATIN MOUNTAINS POST-MIDDLE MIOCENE FOLDING ood-basalt flows of the Columbia River Basalt Group form the bulk of the Po land Hills, and they are folded into a broad, northwest-striking anticline. The southwest limb of the anticline dips 5–15° toward the Tualatin basin, where a similar, thick Columbia River Basalt Group section is encountered beneath fine-grained basin sediments in deep water wells (http://or.water.usgs.gov/projs_dir/crbg/). The northeast limb dips 10–15° toward the Portland basin, also underlain by Columbia River Basalt Group. The tunnel does not extend far enough to the northeast to intersect the presumed location of the Portland Hills Fault along the base of the Portland Hills. Folding apparently was underway during emplacement of the Columbia River Basalt Group. Flows of the basalt of Ginkgo of the Frenchman Springs Member of the Wanapum Basalt (Twfg) are missing on the crest of the anticline, whereas younger basalt of Sand Hollow of the Frenchman Springs Member (Twfs) rest directly on the Sentinel Bluffs Member of the Grande Rond Basalt on the crest of the anticline. Flexural slip deformation of Columbia River Basalt Group flows was noted as sheared and slickensided interbeds throughout the sequence. Shortening along the tunnel profile due only to folding was determined by restoring the top of the Sentinel Bluffs Member to horizontal and comparing it to

its present length. Calculated shortening is about 1%, or an average post-15.6 Ma POST-MIDDLE MIOCENE THRUSTING The exploratory borings disclosed thrust faults that juxtaposed Columbia River Basalt Group units in the Sylvan area and farther west, beneath interlayered Boring flows and Pleistocene sediments (Peterson and Squier Associates, 1993). Tunneling exposed these faulted sections, and our mapping has established displacements o some of the faults. At Sylvan, the Columbia River Basalt Group flows are offset by a west-dipping thrust fault, which displaces Winter Water member (Tgww) several hundred meters eastward over Sentinel Bluffs Member flows near survey station 835+00. We name this fault the Brickworks Thrust for a defunct brick factory originally located above the fault. The fault dips 22° southwest toward the Tualatin basin, but well control in the basin (http://or.water.usgs.gov/projs_dir/crbg/) indicates the Columbia River Basalt Group basalt section is deeper than the projecte hanging wall to the west. Although not encountered in the tunnel, boreholes south of the 260-foot-deep Washington Park MAX Light Rail station disclosed thrust faults extending a few kilometers south to the Tanner Creek canyon, now occupied by US Highway 26. Thrusting there appears related to a component of north south northeast-dipping thrust fault or reverse fault at depth. This geometry is consistent the east side of the Sylvan Fault a few kilometers north of the tunnel (Madin an others, 2008). Sub-horizontal fault-zone breccia encountered in a boring in the upper part of the hanging wall block is interpreted as an extensional fault in the hanging wall anticline (partly removed by erosion). Columbia River Basalt Grou flows in the thrust sheet are eroded and unconformably overlain by Neogene mu stone and 1-my-old basalt flows of the Boring Volcanic Field, both of which dip west on the flank of the anticline. Colluvium and Late Pleistocene loess unconform-

ably overlie tilted older Pleistocene rocks and appear to be undeformed by the thrust PLEISTOCENE FOLDING Above the Brickworks Thrust (between survey stations 815+00 and 830+00), young Boring flows dip southwest about 8° toward the apparent source vent for the flows, which is marked by a large breccia pile cored by a 20-m-wide basaltic dike. The intimate association of the Qbsh flows with breccia of the vent complex strongly suggests they were erupted from that source. Rather than flowing uphill from the source, it is likely that the ~1-Ma Boring lavas have been tilted as a result of continued folding and thrusting of the Portland Hills anticline. The flows overlie the southwest-dipping Brickworks Thrust, but map relations do not permit the large slip on the thrust fault that is required to cause the tilting. If the tilt was caused by slip on a deeper, northeast-dipping master thrust fault, then the displacement would depend on the dip of the fault. Using a fault propagation fold model, a fault dipping 30° northeast requires 140 m of slip to produce the observed tilt (70 m uplift at the northeast end of the 1-Ma Qbsh flows). A vertical fault requires 70 m of slip to produce the observed 8° tilt, or 0.07 mm/yr, and a fault dipping at 45° requires 97 m

of slip since 1 Ma, or an average rate of about 0.09 mm/yr. PLEISTOCENE HIGH-ANGLE FAULTING The Pleistocene basalt flows of the Boring Volcanic Field and interbedded sediments are cut by three near vertical strands of the northwest-trending Sylvan Fau between survey stations 800+00 and 815+00. Measured fault trends and slip dire tions, where known, are shown on the cross section. Flows and pebbly mudstone along the Central Sylvan Fault strand (815+00) are tilted to vertical (fig. 7), with tops to the west, and faulted against weathered Grande Ronde Basalt. The Grand Ronde Basalt is out of place, 76-100 m vertically above projected Grande Ronde Basalt at depth, and it has been thrust eastward over a 1.1-Ma basalt flow. Slickensides on fault and vertical bedding surfaces are sub-horizontal and oblique, suggesting a component of strike-slip motion.

At survey station 803+00, the West Sylvan Fault offsets the 1.17-Ma Basalt of not offset a ~ 1-Ma flow overlying the colluvium. This part of the upper flow is not angle fault are consistent with thrusting, while both horizontal and oblique slickenexposed in the tunnel, so the relations are equivocal. The 120-ka basalt flow of Elk sides on the high-angle faults indicate complex motion.

Point, which is exposed at the west portal, is cut by two zones of vertical shearing a survey stations 800+00 and 802+00, just west of the buried strand of the West Madin and others, 2008) and show similar up-to-the northeast offsets. We interpret east-dipping master fault at depth, which is consistent with the geophysical models of Blakely and others (2000, 2004). This interpretation is also consistent with the present GPS velocity field and focal mechanisms of local seismicity (McCaffrey and others, 2007). The geometric relation between the steep Sylvan Fault and the ow-angle thrust fault in the Columbia River Basalt Group is uncertain. As mapped, the Brickworks Thrust appears older than the Sylvan Fault. In our cross section showing inferred deeper structure, the Sylvan Fault strands cut the Brickworks Portland Hills on the east is unknown. Blakely and others (2004) suggest the Sylvan

POSSIBLE NON-TECTONIC SOURCES OF DEFORMATION Some of the deformation near survey station 815+00 could reflect uplift and shoul dering aside of older strata by rising magma during construction of the vent complex. However, the tops of the vertical beds dip toward the vent, which seems unlikely from forceful intrusion. Landsliding is another possibility, with Columbia River Basalt Group sliding downhill onto the 1.15-Ma basalt flow before eruption of the 1.1-Ma flows. Large deep-seated landslides are common in the Tualatin etry. The deformation zones instead correlate with mapped faults of regional extent. In those zones, near-vent pyroclastic rocks abut sheared, steeply dipping bedded silalong a steep contact, and vertical faults with horizontal slickensides are at right angles to the local slope. The 8° dip of the Boring flows toward the vent between survey stations 815+00 and 830+00 could be initial dip, but the flow package

The faults have been active in the Quaternary, but slip rates are slow. Only vertical slip rates can be determined; strike-slip offsets cannot be determined from the geology in the tunnel. Deformation recorded by the Columbia River Basalt Group nas continued into the Late Pleistocene (after 120,000 years ago). Earthquakes (fi 1) and crustal motion measured by GPS (McCaffrey and others, 2007) indicate regional deformation is continuing today, but no data from the fault zones are ylvan Fault have been recognized in recent high resolution topography from the Oregon Lidar Consortium, which has relative elevation uncertainties of less than a decimeter (Madin and others, 2008). No trenching has been done to determine if the ylvan Fault has had Holocene movement.

FAULT DISPLACEMENT AND SLIP RATES Fault Displacement Unit Average Slip Rate Brickworks Thrust ≥ 500 m 15-Ma CRBG^a Quaternary faults master thrust 70–140 m 1-Ma flow 0.07-0.14 mm/yr^c West Sylvan Flt. 7–20 m 1.1-Ma flow $0.01 - 0.02 \text{ mm/yr}^{d}$ $0.07 - 0.08 \text{ mm/yr}^{\text{e}}$ Central Sylvan Flt. 76–100 m 1.16-Ma flow 0.15–0.24 mm/yr^f Quaternary activity uncertain Using a fault propagation fold model, fault slip at depth depends on fault dip. 30°

dip = 140 m of slip, $90^{\circ} dip = 70 \text{ m of slip to produce } 8^{\circ} \text{ west tilt of } 1\text{-Ma Qbsh}$ The West Sylvan and Central Sylvan Faults are splays and thus the slip rates are

Figure 7. Interpretation of Central Sylvan Fault in tunnel. Weathered Grande Ronde Basalt, Grande Ronde Basalt colluvium, and channel deposits fining upward nto gray mudstone that are exposed between survey stations 815+20 and 815+25 are interpreted as a stratigraphic section, now vertical, with tops to the west. The stratigraphic section is repeated by near vertical faulting and to the west, is highly oxidized bright red where it is overlain by a steeply dipping basalt flow of the Boring Volcanic Field near survey station 814+00. The vertical section is thrust eastward over a 1.15-Ma Boring basalt flow, with sheared mudstone along the

rates for the faults bounding the western flank of the Tualatin Mountains provide useful constrains on deformation history for probabilistic seismic hazard assessment of the greater Portland area.

120-ka flow from survey station 781+84 is from this cut.

and as loess (yellow on the cross sections). Flows of the Columbia River Basalt Group were erupted from fissure vents n eastern Oregon and Washington and covered large parts of Oregon, Washington, and Idaho. A detailed stratigraphy of the Columbia River Basalt Group has been defined on the basis of geologic mapping, geochemistry, and paleomagnetism (Swanson and others, 1979; Beeson and others, 1985; Reidel and others, 1989; Reidel, 2005). Many of these flows entered the northern Willamette Valley, where two formations, the Grande Ronde Basalt and the overlying Wanapum Basalt are recognized. Both formations are encountered in the tunnel and boreholes. The Frenchman Springs Member of the Wanapum during the Jaramillo Subchron (fig. 6). A large dike-like body, unit Qbshi Basalt is represented by the basalt of Sand Hollow (Twfs) and the basalt of Ginkgo (Twfg) of Mackin (1961). The Grande Ronde Basalt is represented by

Its chemical composition is distinctly different than the flows but we include hree flows of the Sentinel Bluffs Member (Tgsb) of Reidel (2005), which the dike in unit Qbsh because of its similar age, normal magnetic polarity, overlies three flows of the Winter Water member (Tgww) of Tolan and others and location in the center of unit Qbsh. 2009) and Reidel and others (1989). Exposed in boreholes below the tunnel is a flow of the underlying Ortley member (Tgo) of Tolan and others (2009) and polarity and lower LILE contents than the other tunnel units. The flows are Reidel and others (1989). Flow-top breccias, entablatures, and colonnades typical of Columbia River Basalt Group flows (see Tolan and others, 2009) vere mapped throughout the tunnel and boreholes (fig. 5A), which along with chemical identification of Columbia River Basalt Group flows, provide an excellent stratigraphic framework. In the western third of the tunnel, the Columbia River Basalt Group is overlain by Pleistocene basalt and basaltic andesite flows of the Boring Volcanic Field of Evarts and others (2009), hereafter referred to as the Boring this rock with chemically similar flows in unit Qbcm. Volcanic Field, which are interbedded with fine-grained continental sediments, debris flows, and colluvium. A thick sedimentary sequence separates the oldest Boring flow from the underlying Columbia River Basalt 1981; Beeson and others, 1991; Madin, 1990; Madin and others, 2008). Group and appears to be in part fluvial silt and fine sand, locally channelized Boreholes show the youngest Boring flow is overlain by the silt and and interbedded with debris-flow deposits containing abundant basalt clasts of interfingers with the upper part of the loess sequence. The light-gray loess weathered Columbia River Basalt Group (figs. 5B,C). The Pleistocene flows overlies an older silt sequence with paleosols that rests on the 1-Ma flows and in the tunnel possess chemically similar calc-alkaline compositions, but map may interfinger with them. The loess was deposited during Pleistocene glacial relations, minor chemical differences, paleomagnetic measurements, and intervals by strong east winds coming out of the Columbia Gorge, and the Ar/Ar age determinations indicate that the flows represent 3 or possibly 4 Tualatin Mountains were the first major barrier encountered by the silt-laden

from the center. Flows and breccias of the basalt of Sunset Hill have greater abundances of large-ion-lithophile elements (LILE) K₂O, Ba, and Sr than the younger basaltic andesite (table 2). Two of the **Qbsh** flows are dated at slightly older than 1 Ma, have normal magnetic polarity, and evidently erupted intrudes breccia east of Sylvan Creek and may mark the vent for these flows. The basalt of Cornell Mountain consists of basalts with reversed magnetic faulted and buried by flows of unit Qbsh. No vent for Qbcm flows has been identified, although Cornell Mountain to the north may be the source. Two samples gave virtually identical ⁴⁰Ar/³⁹Ar plateau ages of 1.15 and 1.17 Ma (table 2). A third sample contained abundant excess argon and did not yield a plateau. We interpret its isochron age of 1.41±0.12 Ma as a maximum, but it differs sufficiently from our other determinations to suggest that it represents an older eruptive event. Because of the age uncertainty, however, we include A thick blanket of structureless, pale-gray to buff quartzo-feldspathic micaceous aeolian silt, or loess, covers most of the Portland Hills (Lentz,

viewed by Sean Bemis and Ian Madin

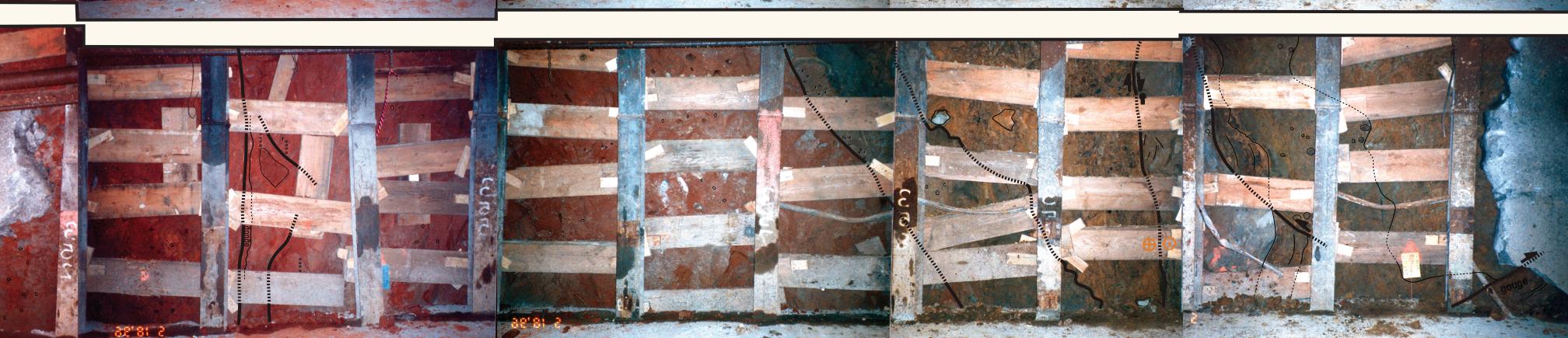
GEOLOGIC CROSS SECTION THROUGH THE PORTLAND HILLS, OREGON

in North America - 260')

EXPLANATION

905+00 TriMet survey station in feet (90,500 feet) from

western end of line; + is location of survey



massive very red

pebbly mudstone

Fault 350°/89E, slickenside rakes on fault plane 90° and 0°

South Wall of Eastbound Bore; photo reversed to compare with profile above

Basalt

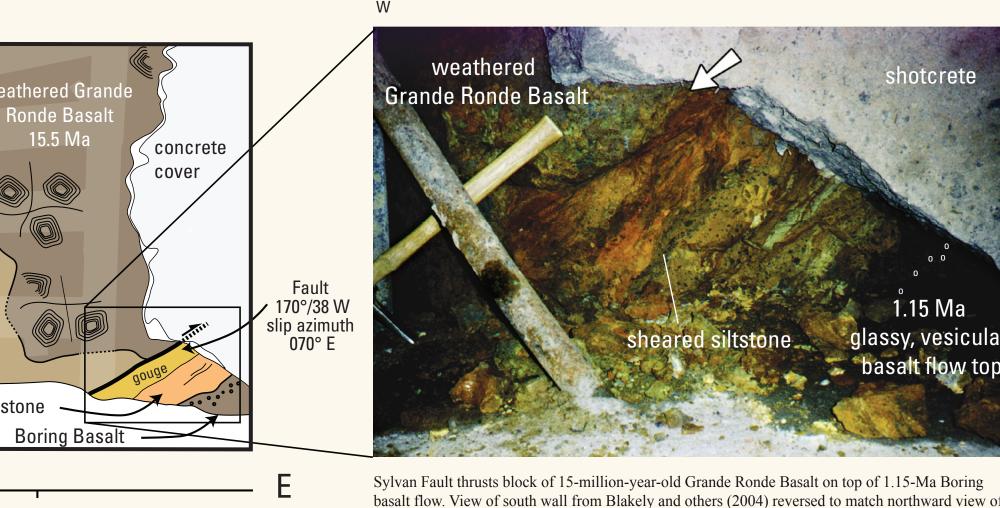
channel deposit?

815+20

¹Portland State University, ²Shannon and Wilson, Inc., ³U.S. Geological Survey

colluvium/

dark red-gray



100 feet = 30.48 meters

no vertical exaggeration

Artificial fill (Holocene)—Gravel, sand, silt, and clay fills with subordinate amounts of construction debris SURFICIAL DEPOSITS Loess (Quaternary)—Quartzo-feldspathic silt that mantle Tualatin Mountains (Portland Hills). Loess up to 20 m thick covers most slopes above about 100 m in elevation. Previous workers (Trimble, 1963; Schlicker and Deacon, 1967; Lentz, 1981; Madin, 1990) have mapped general distribution of loess. Loess was deposited between 2.6 Ma and 17 ka based on correlations of paleosols to regional glacial history and on inferred stratigraphic relations with Boring volcanic rocks and Pleistocene flood sediment. Subdivided into the following: Younger loess (Late Pleistocene)—Light-gray to buff quartzofeldspathic micaceous silt, structureless, forms top of loess sequence beneath modern soil, rests on top of 120-ka basalt flow of Elk Point and older loess deposits, highly variable thickness, up to 20 m on the crest of the Portland Hills Older loess (Pleistocene)—Brown-gray to red brown quartzofeldspathic micaceous silt, contains paleosols, with strong ped structures, locally bioturbated with small weathered basalt clasts; may include laterite developed on underlying Colum bia River Basalt Group flows and fine-grained fluvial sediments. Deposited on Columbia River Basalt Group, older landslide deposits, and 0.97–1.05-Ma Basalt of Sunset Hill Slope or landslide deposits (Quaternary)—Diamict in subsurface consisting of mixed loess, paleosols, and weathered

basalt clasts. Forms large deposit beneath loess at Washington

Park Station and adjacent zoo; may include colluvium and

disturbed Neogene sediments and may be part of a larger

DESCRIPTION OF MAP UNITS*

Modified from Beeson and others (1991)

VOLCANIC ROCKS OF THE BORING VOLCANIC FIELD Rocks of the Boring Volcanic Field of Evarts and others (2009) (**Pleistocene**)—Light-gray to gray, diktytaxitic, olivine-phyric (less commonly plagioclase-phyric) basalt and basaltic andesite flows erupted from a series of local vents. Eruptive activity built cones (for example, Elk Point) composed of interstratified cinders and lava. Lava flows typically display blocky to columnar jointing and, if preserved, vesicular flow tops. Flows of the Boring Volcanic Field can be distinguished from older basalt units on the basis of physical appearance, stratigraphic position, lithology, chemical composition, and magnetic polarity (Beeson and others, 1989b; Peterson and Squier Associates, 1993; Evarts and others, 2009). Subdivided into

Basaltic andesite of Elk Point (Pleistocene)—Gray basaltic andesite flow at west portal of tunnel, flat lying, fills paleochannel west of the West Sylvan Fault; flow top breccia (highlighted in dark pink); Ar/Ar age of 120±15 ka; unit has normal magnetic polarity (tables 1 and 2) **Basalt of Sunset Hill (Pleistocene)**—Gray basalt to basaltic andesite flows and interfingering gray, brown, red and black glassy flow breccia (highlighted in dark pink); unit forms conical pile about 75 m high at survey station 810+00, composed of breccia and interbedded flanking flows which appear to comprise a vent complex. Edifice is buried by loess. Ar/Ar age of 1.048 Ma. Unit has normal magnetic polarity (tables 1 Qbshi Basalt dike (Pleistocene)—Gray basalt forming large vertical basalt dike intruding unit **Qbsh**. Dike has Ar/Ar age of 0.971 Ma. Unit has normal polarity Basalt of Cornell Mountain (Pleistocene)—Basalt to basaltic andesite flow, flow breccia (highlighted in dark pink), and agglomerate forming irregular, eroded (?) edifice; underlies

pasalt of Sunset Hill (Qbsh) and is distinguished from it by

(Swanson and others, 1979) and the formations to be further lower LILE contents; Ar/Ar ages of 1.15 to 1.41 Ma obtained at survey stations 817+31 and 807+73. Unit has reversed subdivided into mappable members and units (Swanson and others, 1979; Beeson and others, 1985; Reidel and others, magnetic polarity (tables 1 and 2) 1989). Members and units belonging to the Wanapum Basalt **BASIN-FILL DEPOSITS** and Grande Ronde Basalt, two of the five Columbia River Neogene sedimentary rocks (Pleistocene to Miocene)—Friable Basalt Group formations, are present within the map area an to weak, massive to thinly bedded, fluvial siltstone, claystone have a collective thickness ranging up to 205 m. Geochemical and fine sandstone. Unit QTs in tunnel underlies and interfin data used to distinguish Columbia River Basalt Group formagers with basalt of Cornell Mountain (Qbcm) and basalt of tions and flows in this area are summarized in Beeson and Sunset Hill (Qbsh). Mineralogy of borehole samples is others (1989b). Divided into the following: quartzo-feldspathic. Locally pebbly, includes debris flows, Wanapum Basalt (middle Miocene) and colluvium. Previous workers have mapped equivalent Frenchman Springs Member rocks as Troutdale Formation (Trimble, 1963; Schlicker and **Basalt of Sand Hollow of Mackin (1961)**—Severely Deacon, 1967), Sandy River Mudstone (Trimble, 1963), or

Inferred master thrust dips east (Blakely and others, 2004)

1989; 2009). Flows entered western Oregon by way of a wide

gap in the northern Oregon Miocene Cascade Range (Beeson

ences and variations in the geochemical, paleomagnetic, and

lithologic properties of Columbia River Basalt Group flows

allow them to be formally divided into five formations

and others, 1985; Beeson and Tolan, 1990). Significant differ-

weathered to completely decomposed sparsely plagioclase Sandy River Mudstone equivalent (Madin, 1990; Peterson and phyric basalt in boreholes (Peterson and Squier Associate Squier Associates, 1993), and undifferentiated sediments 1993). Regionally, these flows are typically blocky to colum (Beeson and others, 1989b). Local silt and pebbly sand nar jointed but occasionally display entablature/colonnade equivalent to the Vantage Sandstone Member of the Ellens jointing. Flows are fine to coarse grained, occasionally dikty burg Formation between Wanapum Basalt and Grande Ronde taxitic, and sparsely plagioclase-phyric, with phenocrysts up Basalt are included in this unit to 2 cm in size. At least one flow is present in the subsurface BEDROCK Columbia River Basalt Group (Miocene)—Tholeiitic floodand composition (Beeson and others, 1989b). Beeson and basalt flows that were erupted from linear fissure systems in northeastern Oregon, eastern Washington, and western Idaho between 17 and 6 Ma (Swanson and others, 1979; Tolan and others, 1989, 2009). Individual flows cover thousands to tens jointed plagioclase-phyric basalt, commonly displaying of thousands of square kilometers and range from hundreds to thousands of cubic kilometers in volume (Tolan and others,

Sand Hollow flows (Twfs) can be distinguished from Gingk flows (Twfg) on the basis of stratigraphic position, lithology others (1985) report an average K-Ar date of 15.3 Ma for this Basalt of Gingko of Mackin (1961)—Blocky to columnar well-formed prismatic colonnades. Fresh exposures are dark gray to black, weathered surfaces commonly reddish brown to gray. At least one flow is present in the subsurface and is typically medium-grained, plagioclase-microphyric basalt with laths < 0.1 cm in size, and abundantly plagioclase-physical with phenocrysts and glomerocrysts ranging from 0.3 to 2.5 cm in size. Thickness of unit is 15 m or less within map area

Gingko flows can be distinguished from plagioclase-phyric Sand Hollow flows (Twfg) on the combined basis of stratigraphic position, composition (Beeson and others, 1989b), and a southeast and down excursional paleomagnetic direction (Beeson and others, 1985)

Grande Ronde Basalt (middle Miocene) Sentinel Bluffs Member of Reidel (2005)—Blocky to columnar jointed, light- to dark-gray basaltic andesite flows, rarely with entablature and colonnade jointing. Two flow types are recognized in the subsurface, each consisting of two or three flow units, locally separated by thin sedimentary interbeds and vesicular flow-tops (highlighted in dark green shading). Upper flow (Tgsb2) is fine grained to medium grained, commonly diktytaxitic, and aphyric. Lower flow

(Tgsb1) is typically fine grained to medium grained and sparsely plagioclase-phyric, with small (<0.5 cm), tabular plagioclase phenocrysts. Unit is up to 50 m thick within mag area. Sentinel Bluffs flows are distinguished from both younger Wanapum Basalt flows and older Grande Ronde Basalt flows on the basis of stratigraphic position, composi tion (Beeson and others, 1989b), lithology, and normal paleomagnetic polarity (see Reidel and others, 1989; Beeson and others, 1989a; Reidel, 2005). Long and Duncan (1982) report ⁴⁰Ar/³⁹Ar age of approximately 15.6 Ma for youngest Sentinel Bluffs flow on the Columbia Plateau of eastern Washing ton, about 200 km east of Portland Winter Water member of Reidel and others (1989)—Columnar and entablature/colonnade-jointed

abundantly phyric, with small (<0.3 cm) plagioclase

glomerocrysts that often display distinctive radial or

spoke-shaped habit. Distribution of glomerocrysts is often

exposures 5 km north of tunnel. Unit contains flows of both the Grouse Creek and Wapshilla Ridge units of Reidel and others (1989) assigned to R2 magnetostratigraphic unit of the Columbia River Basalt Group dark-gray to black basaltic andesite flows with vesicular flow tops (highlighted in dark blue shading). Two flows are presen in the tunnel; both are glassy to fine grained and phyric to

Regional correlation within the Frenchman Springs Member of the Columbia River Basalt Group-New insights into the middle Miocene tectonics of northwestern Oregon: Oregon Geology, v. 47, Fleck, R.J., Sutter, J.F., and Elliot, D.H., 1977, Interpretation of Beeson, M.H., and Tolan, T.L., 1990, The Columbia River Basalt Group in the Cascade Range–A middle Miocene reference datum

Lentz, R.T., 1981, The petrology and stratigraphy of the Portland Hills for structural analysis: Journal of Geophysical Research, v. 95, no.

Silt—a Pacific Northwest loess: Oregon Geology, v. 43, no. 1, p. uneven and they tend to be less abundant in basal portion of B12, p. 19,547–19,559. flow. Unit thickness ranges from 7.5 to 30 m within map area

Winter Water flows are distinguished from other Grand Ronde

flows on the basis of lithology, composition (Beeson and

shallow normal paleomagnetic direction (see Reidel and

others, 1989b), stratigraphic position, and a northwest and

others (1989); Beeson and others (1989a); Wells and others

Ortley member of Reidel and others (1989)—Entablature

deep drill holes below the tunnel. Commonly glassy to very

fine grained and aphyric. Unit thickness ranges from 7.5 to

>60 m in the Portland Hills. Compositionally (Beeson and

guished on the basis of normal paleomagnetic polarity for

Swanson and others (1979)—Shown only in cross section

Ortley flows (see Reidel and others, 1989; Beeson and others,

others, 1989b) and lithologically similar to older Grouse

Creek unit of Reidel and others (1989) but can be distin-

Grande Ronde Basalt, R2 reversely polarized unit of

showing deeper structure, flows projected from surface

/colonnade-jointed dark-gray to black basaltic andesite flow i

Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989a, The Columbia Long, P.E., and Duncan, R.A., 1982, 40Ar/39Ar ages of Columbia River Basalt Group in western Oregon—geologic structures and other factors that controlled flow emplacement patterns, in Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 223–246. Beeson, M.H., Tolan T.L., and Madin, I.P., 1989b, Geologic map of the Lake Oswego quadrangle, Clackamas, Multnomah and Washington Madin, I.P., 1990, Earthquake-hazard geology maps of the Portland

Counties, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map Series GMS–59, scale 1:24,000. Beeson, M.H., Tolan T.L., and Madin, I.P., 1991, Geologic map of the Madin, I.P., Ma, Lina, and Niewendorp, Clark A., 2008, Preliminary Portland quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geologic Map Series GMS-75, scale 1:24.000. Blakely, R.J., Wells, R.E., Cruikshank, K., Johnson, A., and Beeson, M., 2004, Gravity study through the Tualatin Mountains, Oregon:

Geological Society of America Bulletin, v. 107, p. 1051–1062.

Light Rail Tunnel: an evaluation 5 years after completion [abs.],

Evarts, R.C., Conrey, R.M., Fleck, R.J., and Hagstrum, J.T., 2009, The

Burns, S.F. Peterson, G.L., and Walsh, K., 2001, Portland's Westside

GSA Abstracts with Programs, v. 33, no. 6, p. 47.

Understanding crustal structure and earthquake hazards in th Portland urban area: Bulletin of the Seismological Society of America, v. 94, no. 4, p.1402–1409. Blakely, R.J., Wells, R.E., Tolan, T.L., Beeson, M.H., Trehu, A.M., and Liberty, L.M., 2000, New aeromagnetic data reveal large strike-slip (?) faults in the northern Willamette Valley, Oregon: Geological Society of America Bulletin, v. 112, p. 1225–1233. Blakely, R.J., Wells, R.E., Yelin, T.S., Madin, I.P., and Beeson, M.H., Washington—Constraints from low-altitude aeromagnetic data:

landscape of the Pacific Northwest: Geological Society of America discordant ⁴⁰Ar/³⁹Ar age-spectra of Mesozoic tholeiites from Antarctica: Geochimica Cosmochimica Acta, v. 41, p. 15–32.

River basalt from deep boreholes in south-central Washington [abs.]: Alaska Science Conference, 33rd, Fairbanks, AK., Proceedings, p. 119 (also EOS, v. 64, no. 9 (March 1, 1983), p. 90). Mackin, J.H., 1961, A stratigraphic section in the Yakima Basalt and Division of Mines and Geology Report of Investigations, 19, 45 p. metropolitan area: Oregon Department of Geology and Mineral Industries Open-File Report O-90-2, 21 p., 8 maps, scale 1:24,000. geologic map of the Linnton 7.5' quadrangle, Multnomah and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Map O-08-06, scale 1:24,000. McCaffrey, R., Qamar, A.I., King, R.W., Wells, R.E., Ning, Z.,

Williams, C.A., Stevens, C.W., Vollick, J.J., and Zwick, P.C., 2007,

Fault locking, block rotation, and crustal deformation in the Pacific Northwest: Geophysical Journal International, v. 169, p. 1315–1340. McIntyre, G.A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Journal of Geophysical Research, v. 71, no. 22, p. 5459–5468. Peterson, G.L., and Squier Associates, 1993, Westside LRT Tunnel Line Section 5A, Final Geotechnical Interpretive Report Unpublished report for Tri-Met, Portland, Oregon, 300 p.

Peterson, G.L., and Walsh, Ken, 1996, Geology of the Tri-Met LRT tunnel through the Tualatin Mountains, Portland, Oregon [abs.]: Geological Society of America Abstracts with Programs, Cordilleran Section, p. 100–101. Reidel S.P., 2005, A lava flow without a source–the Cohassett flow and its compositional components, Sentinel Bluffs Member, Columbia River Basalt Group: Journal of Geology, v. 113, p. 1–21. Boring Volcanic Field of the Portland-Vancouver area, Oregon and Reidel, S.P., Tolan, T.L., Hooper, P.R., Beeson, M.H., Fecht, K.R.,

setting, in O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds.,

Basalt, Columbia River Basalt Group; stratigraphic description and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 21–53. Schlicker, H.G., and Deacon, R.J., 1967, Engineering geology of the Tualatin Valley region, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 60, 103 p. Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979,

Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457–G, 59 Tolan, T.L., and Beeson, M.H., 1984, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorgo and their relationship to the Troutdale Formation: Geologica Society of America Bulletin, v. 95, no. 4, p. 463–477. Tolan, T.L., Martin, B.S., Reidel, S.P., Kauffman, J.D., Garwood, D.L. and Anderson, J.L., 2009, Stratigraphy and tectonics of the central and eastern portions of the Columbia River Flood-Basalt Province—An overview of our current state of knowledge, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards: Geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 645–672 doi: 10.1130/2009.fl d015(29). Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, in Reide S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society o America Special Paper 239, p. 1–20. Trimble, D.E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

Walsh, K., Rice, P.M., Peterson, G.L., Beeson, M.H., Blouke, K.J., 1996, As-built geology of the Tri-Met Westside Light Rail projec tunnel through the Tualatin Mountains, Portland, Oregon: Association of Engineering Geologists Program and Abstracts, Wells, R.E., Simpson, R.W., Bentley, R.D., Beeson, M.H., Mangan, M.T., and Wright, T.L., 1989, Correlation of Miocene flows of the Columbia River Basalt Group from the central Columbia River Plateau to the coast of Oregon and Washington, in Hooper, P., and Reidel, S., eds., Volcanism and tectonism in the Columbia River flood basalt province: Geological Society of America Special

A Tunnel Runs Through It—An Inside View of the Tualatin Mountains, Oregon

prehistoric landslide

thickness of Boring and CRBG flows at depth projected from WASH 330, a deep well 5 km to NW (http://or.water.usgs.gov/projs_dir/crbg/)

Ken Walsh¹. Garv L. Peterson². Marvin H. Beeson¹. Rav E. Wells³. Robert J. Fleck³. Russell C. Evarts³, Alison Duvall³, Richard J. Blakely³, and Scott Burns¹